Upper Limits on Dark Matter in Dwarf Spheroidal Galaxies at VERITAS

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Abstract

Recent data and cosmological models point to a significant fraction of the Universe comprised of Cold Dark Matter (DM), though little is known about it directly. The most likely explanation for Dark Matter is a Weakly Interacting Massive Particle (WIMP) having a mass as low as ~10 GeV to as high as ~10 TeV. Many direct and indirect detection schemes have been proposed to search for the elusive particle. Dwarf Spheroidal Galaxies (dSphs) orbiting the Milky Way Galaxy are suitable targets for indirect DM detection via gamma-rays because the ratio of their gravitational mass to luminous mass is high and their gamma-ray background from other astrophysical sources is low. We present preliminary results on the VERITAS observations of five dSphs. The limit to thermally-averaged DM annihilation velocity-weighted cross-section can then be computed from the gamma-ray flux upper limit.

Observations and Analysis

The table below shows the combined exposure time VERITAS has observed the sources from February 2007 to June 2013. Observations were taken in wobble mode, where the pointing is offset 0.5° from the source position, to increase background statistics. The data was analyzed with the latest version of the VEGAS software package. Cuts on the shower parameters were applied to reduce the cosmic-ray background. Camera images were fit with a 2D Elliptical Gaussian to improve shower reconstruction efficiency. An angular θ0 cut was used to define the source region and an annulus at the same radial offset as the source position but excluding the source region was used to define the background region. Significance was calculated according to the method of Li & Ma5. Counts and flux upper limits were found using the Rolke method with an assumed spectral index of -2.4.

Preliminary Results

<table>
<thead>
<tr>
<th>dSph</th>
<th>Dist. (kpc)</th>
<th>Exp. (hr)</th>
<th>Std. Dev.</th>
<th>UL (cts)</th>
<th>Eث (GeV)</th>
<th>Int. Flux UL (cm⁻² s⁻¹ above 300 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boötes I</td>
<td>62</td>
<td>14.0</td>
<td>-1.04</td>
<td>40.3</td>
<td>170</td>
<td>4.97e-13</td>
</tr>
<tr>
<td>Willman I</td>
<td>38</td>
<td>13.7</td>
<td>-0.63</td>
<td>70.5</td>
<td>180</td>
<td>1.18e-12</td>
</tr>
<tr>
<td>Draco</td>
<td>80</td>
<td>49.9</td>
<td>-1.04</td>
<td>84.1</td>
<td>220</td>
<td>3.41e-13</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>66</td>
<td>59.7</td>
<td>-0.01</td>
<td>79.1</td>
<td>290</td>
<td>3.41e-13</td>
</tr>
<tr>
<td>Segue I</td>
<td>23</td>
<td>91.9</td>
<td>0.72</td>
<td>289.9</td>
<td>150</td>
<td>4.16e-13</td>
</tr>
</tbody>
</table>

The Observatory

VERITAS (the Very Energetic Radiation Imaging Telescope Array System) is an array of four 12 m IACTs located at the Fred Lawrence Whipple Observatory in Amado, AZ (1250 m a.s.l.). Each camera houses 499 Hamamatsu high- QE PMTs and has a field of view of 3.5°. The pixels record the brief flash of Cherenkov radiation when a gamma-ray interacts with the upper atmosphere to produce an extensive air shower. VERITAS is most sensitive over the range of energies from 100 GeV to 30 TeV with an energy resolution of ~15% and an angular resolution of 0.1°. A source with 1% of the Crab Nebula flux can be detected in 25 hrs.

DM Exclusion Curve Calculation¹:

\[ \chi^2 = \frac{1}{2} \sum_{i=1}^{n} \left( \frac{N_{obs} - N_{pred}}{\sigma_{i}} \right)^2 \]

\[ \chi^2_{DM} = \frac{1}{2} \sum_{i=1}^{n} \left( \frac{N_{obs} - N_{DM}}{\sigma_{i}} \right)^2 \]

\[ t_{DM} = \frac{N_{DM}}{\sqrt{N_{obs}}} \]

\[ \ TLC = \frac{\int_{t_{DM}}^{\infty} f_{DM}(t) dt}{\Delta \Omega} \]

• \( \chi^2 \) is the DM annihilation velocity-weighted cross-section
• \( N_{obs} \) is the counts upper limit
• \( f_{DM}(t) \) is the astrophysical J factor defined as the integral of the DM density profile squared along the line of sight (units are GeV cm³)
• \( t_{DM} \) is the observation time
• \( TLC \) is the integral single DM annihilation spectrum times the effective area as functions of energy

References:


Acknowledgements:

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Introduction

Dark matter is an invisible form of matter that comprises 84.5% of the mass of the Universe (25.8% is DM, 4.9% is luminous matter, and 5% is dark energy). Many methods have been employed to identify it:

• Direct searches employ massive high-Z targets looking for the recoil of a dark matter particle off of an atom in the detector (e.g. LUX, XENON100/1T, CDMS, DAMA/LIBRA).
• Accelerator searches use powerful magnets and RF cavities to collide quark-antiquark or quark-antiquark pairs at high enough energies to probe a range of dark matter particle masses (Tevatron, LHC).
• Indirect searches look for the visible byproducts after a dark matter annihilation has occurred. Dark matter is believed to be its own antiparticle and many possible annihilation channels exist, namely quark-antiquark pairs, bosons, leptons, and gamma-rays.

Dwarf Spheroidal Galaxies are small, satellite galaxies to our own with low luminosity (\( L \sim 10^{7} L_{\odot} \)) and mass \( ~10^{7} M_{\odot} \). dSphs are promising targets due to their low mass to light ratio, the minimal contribution of the diffuse background, and their observed low number of dark matter particles.

Segue I dSph recently completed a survey of 25 dwarf spheroidals by the FERMI gamma-ray satellite has completed a survey of 25 dwarf spheroidals and found a combined likelihood limit¹. The other two major Imaging Atmospheric Cherenkov Telescope (IACT) groups, MAGIC and HESS, have both published competitive upper limits on Segue I ¹,¹² and other dwarf spheroidals. The FERMI gamma-ray satellite has completed a survey of 25 dwarf spheroidals and found a combined likelihood limit¹.

Summary

Dwarf Spheroidal Galaxies are likely candidates for indirect DM detection and VERITAS will continue its observing campaign of them. Further data will increase our statistics and drive down the exclusion plot to exclude greater areas of the phase space and make a detection.

The upper limits of the dSphs can be combined with a stacking analysis to give an even more stringent limit in future work.